LA-UR -80-1038

CONF-800537--1

TITLE: THE LASER PROTECTIVE EYEWEAR PROGRAM AT THE LOS ALAMOS SCIENTIFIC LABORATORY

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SUBMITTED TO: For Presentation to
The Industrial Hygiene Conference
Houston, Texas, May 18-23, 1980
(Invited Paper)

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THE LASEP PROTECTIVE EYEWEAR PROGRAM AT THE LOS ALAMOS SCIENTIFIC LABORATORY

D. C. Winburn

Abstract

The proliferation of lasers at Los Alamos focused considerable attention on providing adequate eye protection for experimenters involved in the use of a wide variety of nonionizing radiation. Experiments with fast-pulsed lasers (Nd:YAG, HF, and CO_2) were performed to gain biological threshold data on ocular damage. In parallel, eye protective devices were evaluated, which resulted in the development of lightweight, comfortable spectacles o colored glass filters that can be ground to prescription specifications. Goggle styles are employed in specific applications.

INTRODUCTION

Research in LASL L-Division, formed in 1972, centers on inertial confinement to initiate controlled thermonuclear deuterium-tritium (DT) reactions as a potential source of thermal energy. Available protective eyewear was essentially limited to goggle-styles and to dark plastics or glass. Coatings, now forbidden, were also in use. Only one color glass filter, Schott Optical Glass Company's BG-18, was available (for ruby and/or Nd:YAG), but only in plano and only in frames with opaque sideshields.

Lasers being considered for laser fusion experiments were Nd:glass, HF, and CO_2 at wavelengths of 1.06, 2.7 and 10.6 μm, respectively, as well as ruby (0.67 μm) and iodine (1.3 μm); HeNe (0.63 μm) lasers were in use for alignment. Ultraviolet, dye, and infrared lasers were discussed as potential tools for isotope separation. Metal-oxide laser experiments were in process. In summary, almost the entire spectrum from 0.2 to 11 μm was either covered by lasers in operation or was being seriously considered in experimental programs.

Biological damage thresholds had not been determined by the biophysics community for some of the ultrafast lasers in use, and, consequently, data on maximum permissible exposures (MPE) were not available from the ANSI standard.* LASL's Safety Group, H-3, was aware of the hazards associated with lasers and was following

*Note: ANSI Z136.1 "Safe Use of Lasers," American National Standards Institute, 1430 Broadway, NY, NY 10081.

control guidelines being established by the American National Standards Institute by the Standard ANSI Z136.1 which had not been published.

An effort was launched in the fall of 1972 to determine laser damage thresholds at Los Alamos using L-Division's advanced pulsed-laser systems, particularly Nd:YAG, HF, and CO_2, without interrupting programmatic schedules. In another program suitable protective eyewear was developed to satisfy the needs of laser personnel working routinely in laser laboratories who, at that time, were required to wear cumbersome, uncomfortable, dark-colored eye-protective devices that limited peripheral and direct vision. In evaluating eye protection properties desired, a brief discussion is presented of laser emission hazards, the biological damage threshold experiments, and how the lightweight, corrective eyewear was developed.

LASER RADIATION HAZARDS

Biological damage to laser operating personnel is the obvious concern in evaluating the safety of a laser environment. A secondary concern is the possible ignition of combustible material by the beam, and, in some instances, the physical damage to valuable items in the vicinity. Obviously illumination capable of igniting flammables or of inflicting damage to any materials should be enclosed and operated by remote control. Only lasers of lower power, capable of causing ocular damage but too weak to damage the skin, may be operated at LASL by personnel in the immediate vicinity of the unshielded beam provided they wear eye protection.

Three types, or modes, of laser generated beams are available in our Laboratory: (1) continuous-wattage (cw) or steady beams, (2) single-pulsed beams, repeated at a frequency of less than one pulse per second; and (3) repeatedly pulsed beams, pulsed at a rate higher than one pulse per second. The biological damage mechanisms for each type of beam are different, but two or three mechanisms may be involved in the interactions and the mechanisms could be synergetic. The extent of damage depends on the depth of penetration by the beam, which in turn depends on the wavelength (Fig. 1).* The following types of damage can occur:

- Thermal damage to tissue is the major contributing mechanism resulting from excessive exposure to cw lasers and repeatedly pulsed lasers, depending on repetition rate and length of time of the individual pulse, measured in fractions of a second;
- Mechanical damage to tissue is the major contributing mechanism resulting from excessive exposure to single-pulse lasers if the pulse is fast enough [less than ~100 nanoseconds (100×10^{-9}s)]; and
- Photochemical damage, a minor contributing mechanism in most laser-induced biological reactions.

The wavelength of a lasing medium dictates which ocular component absorbs the light energy if the eye is exposed to a laser beam. The following generalizations apply.

Wavelengths in the "ocular focus" region of the spectrum (0.4 to 1.4 μm) are transmitted through the cornea, lens, and aqueous medium and their intensity is increased by a factor of 100 000 when focused onto retinal tissue.

*L. Goldman and J. Rockwell, "Lasers in Medicine," Gordon and Breach, Science Publishers, Inc., 440 Park Ave., So., New York, NY 10016, 1971.

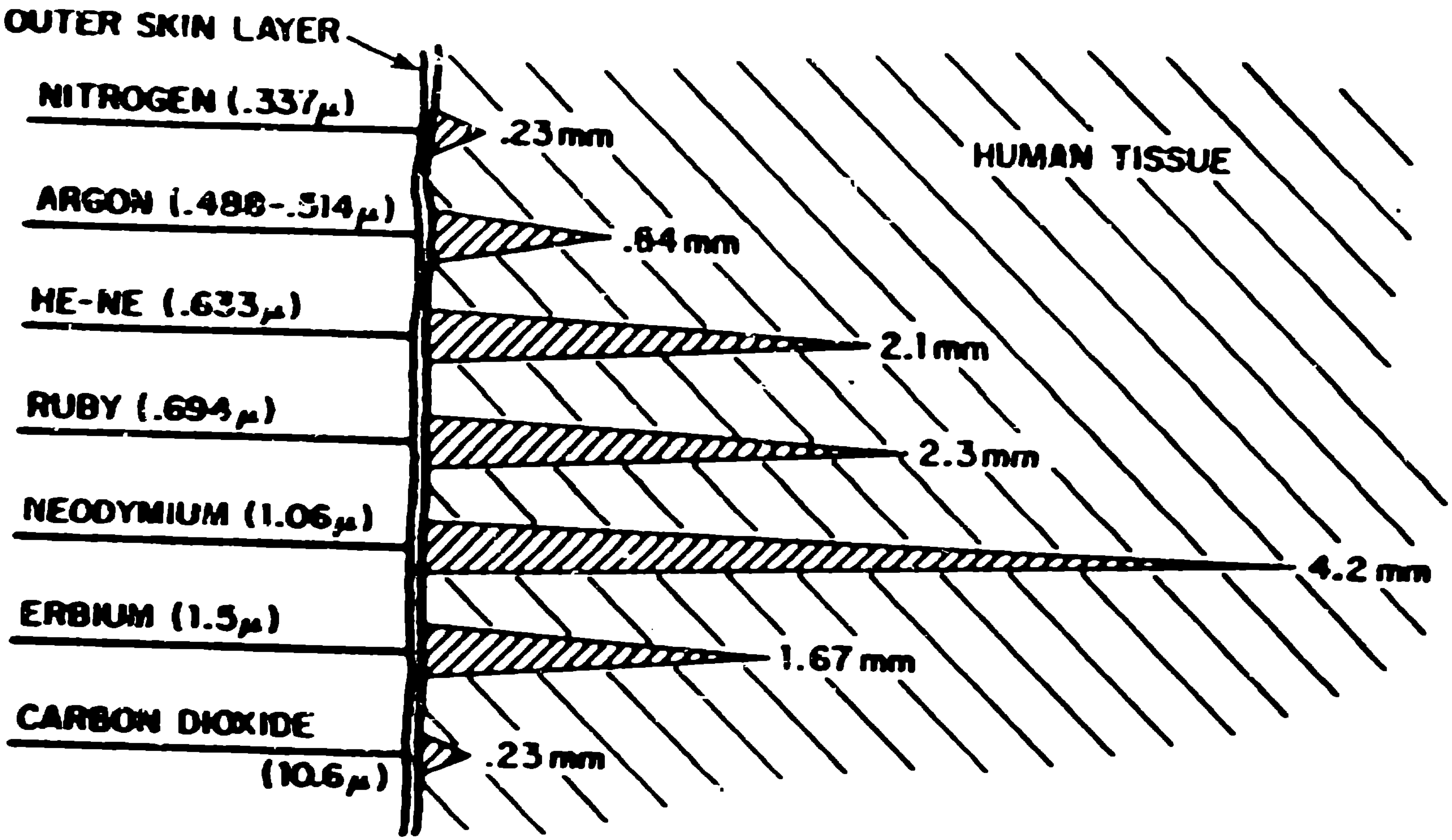

FIG. 1. Penetration depth in human tissue for absorption of 99% of incident energy for various lasers.

Ultraviolet rays (0.2 to 0.4 µm) are absorbed by outer ocular components, particularly the cornea.

Infrared radiation (0.4 µm to 1.0 mm) is also absorbed by the outer ocular components, particularly the cornea.

ANIMAL EXPERIMENTS

In the early days of research essentially no biological threshold damage data were available to determine the maximum exposure levels for the ultrafast pulsed lasers being developed by L-Division. The Division agreed to develop a program with experts in the field of biophysics to determine threshold damage information using live animal tissue and LASL's Nd:YAG, HF, and CO_2 well-characterized pulsed lasers. The eyes of Rhesus monkeys were exposed to the Nd:YAG wavelengths (natural at 1.06 µm and halved at 0.53 µm) which are focusable to the retina; rabbit eyes were exposed to HF (2.7 to 3.0 µm) and CO_2 (10.6 µm) lasers for corneal damage, and pigskin was used for skin experiments with HF and CO_2 lasers. Details of the experiments are described elsewhere,* but a summary of the results is presented below:

* D. C. Winburn, "Biological Damage Threshold Studies," EOSD Magazine, Nov. 1977, p. 19-22.

RETINAL DAMAGE THRESHOLDS
(30 ps pulsed Nd:YAG)

Wavelength (μm)	Spot Size (μm)	Threshold Exposures Into Eye ($\mu J/cm^2$)	On Retina (J/cm^2)
1.064	25	8.7 ± 4.3	2.7
0.532*	25	18.2 ± 8.8	6.5

*Doubled Frequency of 1.064 Radiation.

CORNEAL DAMAGE THRESHOLDS

Laser Wavelength (μm)	Pulsewidth (ns)	Damage Threshold (mJ/cm^2)
2.7 to 3.0	4.0	4 to 7
2.7 to 3.0	100.0	9 to 10
10.6	1.4	5 to 6

SKIN DAMAGE THRESHOLDS

Laser Wavelength (μm)	Pulsewidth (ns)	Damage Threshold (mJ/cm^2)
2.8 to 2.91	100.0	300
10.6	1.4	230

DEVELOPMENT OF CORRECTIVE COLOR FILTER GLASSES

General

The technology of Nd:YAG lasers preceded that of other prospective fusion lasers in the early 1970's, and that wavelength (1.06 μm) was in use as a diagnostic at LASL to develop fast-pulse instrumentation for analyzing the CO_2 systems being developed for fusion experiments. Concern for eye protection from 1.064 μm radiation predominated because the other laser candidates, HF and CO_2, emitted in the wavelengths of 2.7 and 10.6 μm, respectively, which are both outside the ocular focus region. Available eye protective devices for 1.064 μm wavelength consisted of a soft-plastic goggle manufactured by Glendale Optical (GO). The green color restricted luminous transmission to about 45%. American Optical (AO) had a spectacle style device with either blue glass or green plastic lenses, but each had relatively low luminous transmission. The AO frame, however, included opaque sideshields which restricted peripheral vision. The Glendale firm offered a similar device, except that the sideshields were translucent, permitting some peripheral vision, but the plastic lense was dark green. One other firm, Fish-Shurmer Corp., offered round blue glass lenses in a goggle style frame, but luminous transmission was also low and peripheral vision was blocked. Because a large percentage of the laser personnel required corrective eyewear, and some peripheral vision was available, the soft plastic green goggle was the favorite, although all available types were evaluated. Even combinations of one manufacturer's lenses in another's frame were tried. It was recommended by one supervisor in December 1972 that "...comfortable safety glasses combining the best features of the GO and AO spectacles can be created by placing AO glass lenses in GO frames." The possibility of grinding glass filters was suggested so that corrective lenses could be provided, even bifocals if possible.

Discovery of KG-3 for Nd:YAG and HF Protection

Early in 1973 the search for an appropriate filter glass with the qualities required for use in Nd:YAG laser labs produced a candidate: Schott Optical Glass Co., glass filter KG-3. A LASL laser physicist, using the filter in attenuating a 1.06-μm beam during experimentation, observed the high luminous transmission (estimated at 85 to 90%) and adequate attenuation. A local optician recommended that an optical job shop, the Fred Reed Optical Co. in Albuquerque, NM, be contacted as a possible supplier of corrective lenses of KG-3. Experiments with KG-3 proved fruitful and in 1974 a request for bids was sent to Fred Reed Optical (FRD) and all manufacturers of laser eyewear to provide prescription and plano spectacles. Only FRD was able to offer this unique service, and, to my knowledge, continues to be the only source of corrective KG-3 lenses. This firm developed bifocals of the cement-on-segment design and, later, the Ben Franklin bifocal (two-piece). The frame specified was the GO spectacle type with adjustable temples, constructed of sturdy plastic with translucent, broad-band filter, plastic sideshields. The frame and lenses are also acceptable as industrial safety eyewear, meeting ANSI Z87.1 requirements.

The transmission curve of the KG-3 glass is shown in Fig. 2. It was recommended to laser personnel experimenting with hydrogen fluoride (HF) lasers that KG-3 was also a filter for the 2.7-μm wavelength. Because the HF wavelength (actually ranging from 2.6 - 3.1 μm) is absorbed on the cornea of the eye, the attenuation factor need not be as high as that required for the ocular focus region. No other material, glass or plastic, other than KG-3, has been found for HF eye protection that offers such visual clarity, good attenuation, and that can be provided in prescription lenses.

Adapting BG-18 for Ruby, HeNe, and Kr Protection

Studying the transmission curves for Schott Optical Glass Co.'s absorbing color filter glasses for attenuating the ruby wavelength of 0.694 μm, we found that the blue glass, designated BG-18, had good attenuation and an acceptable luminous transmission of ∿ 65%. This glass could be ground into corrective lenses and had an absorption range of several wavelengths below that of ruby. It is used for protection against fairly high power densities (∿ 400 mW/cm^2) of HeNe (0.633 μm) and Kr (0.674 μm) alignment beams, but attenuation is such that the human eye can perceive the red colors from reflective surfaces without exceeding the damage threshold (∿ 10 mW/cm^2) of the cw irradiation. The BG-18 glass also is an excellent filter for Nd:YAG lasers at 1.064 μm, but if that is the only wavelength of interest, KG-3 glass is preferred because it is transparent to white light and does not absorb red color, e.g., control-panel lights. Figure 3 shows the transmission curve for BG-18.

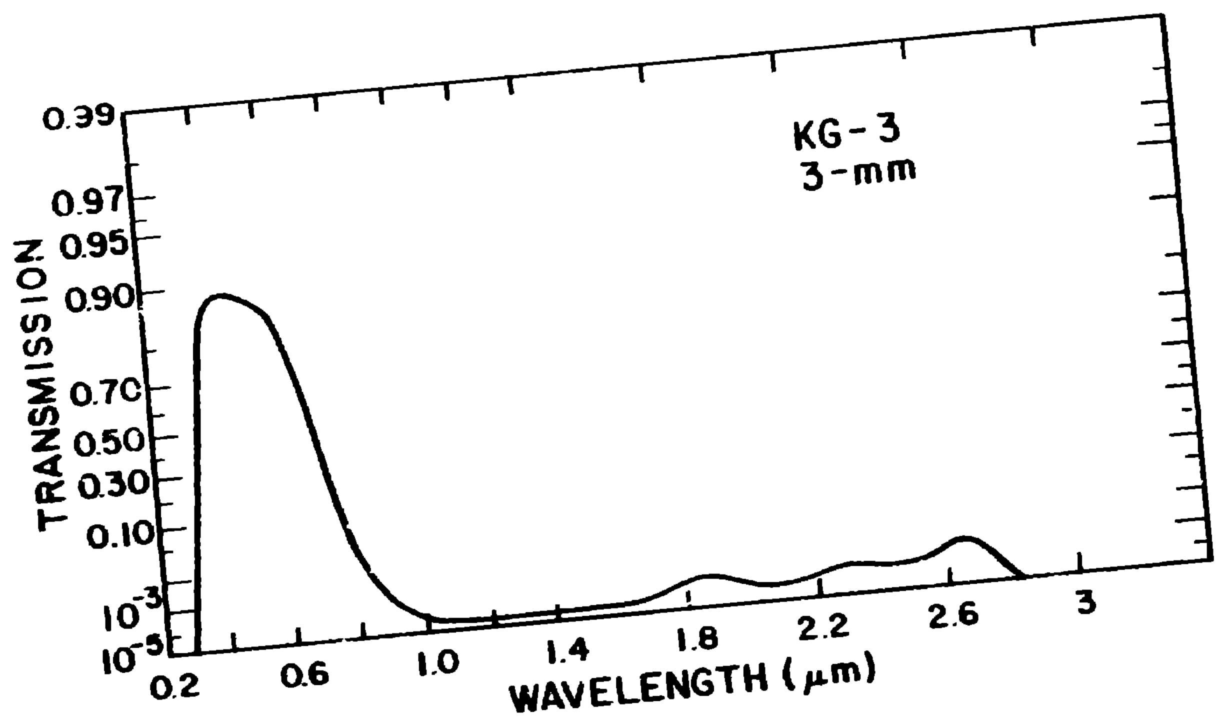

FIG. 2. Transmission curve for KG-3.

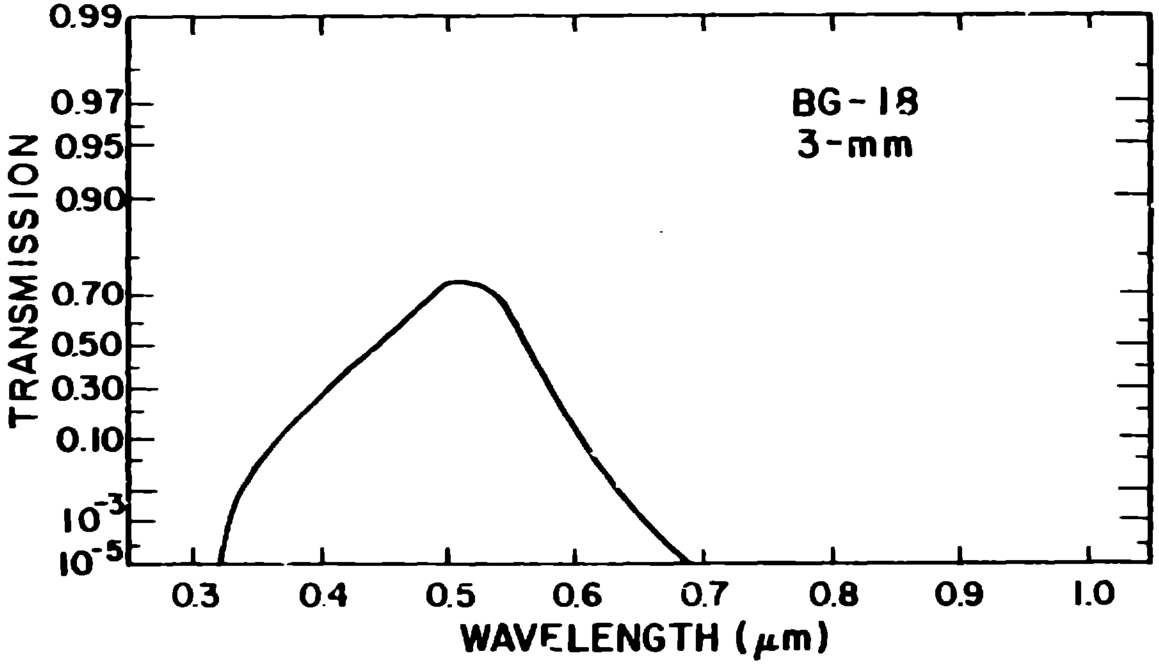

FIG. 3. Transmission curve for BG-18.

Addition of Red, Orange, and Green Glass Series

The addition of a variety of diagnostic (interferometer) lasers, and of materials-processing lasers for use in microballoon target preparation, as well as of tunable dye lasers in research led to the consideration of the cut off filter series of phosphate glass available from the Schott Optical Glass Co. as protective eyewear lenses. Figure 4 shows transmission curves of the series. A specific glass is selected after a single wavelength or range of wavelengths is specified. At 10^{-5} transmission (horizontal line at the bottom of the chart) where the desired wavelength intersects, the transmission curve nearest to the right of the intersection is the glass designation recommended. The glass selected filters all wavelengths to the left of the intercept. The transmission factor of 10^{-5} corresponds to an optical density (OD) of 5. For example, for an argon laser emitting 0.51 µm, the OG-550 glass should be selected, as indicated in Fig. 4. All wavelengths in the range 0.2 to 0.52 µm would be attenuated to a minimum OD of 5.

An explanation is given as to why an optical density of 5 is stipulated. Optical density is the ratio of the base-ten logarithm of incident light to that of transmitted light: $OD = \log_{10} I_i/I_t$, where I_i is the light entering a transmitting medium (filter), and I_t is the transmitted light leaving the medium, both expressed in the same term (mW/cm^2). For instance when I_t, the threshold damage value for the eye, is known, the permissible incident light I_i, can be calculated by using the optical density of 5. Assume that the damage value, I_t, for cw HeNe at 0.63 µm is 10 mW/cm^2.*

*W. Ham, et al., Acta. Opthal. 43, 390 (1965).

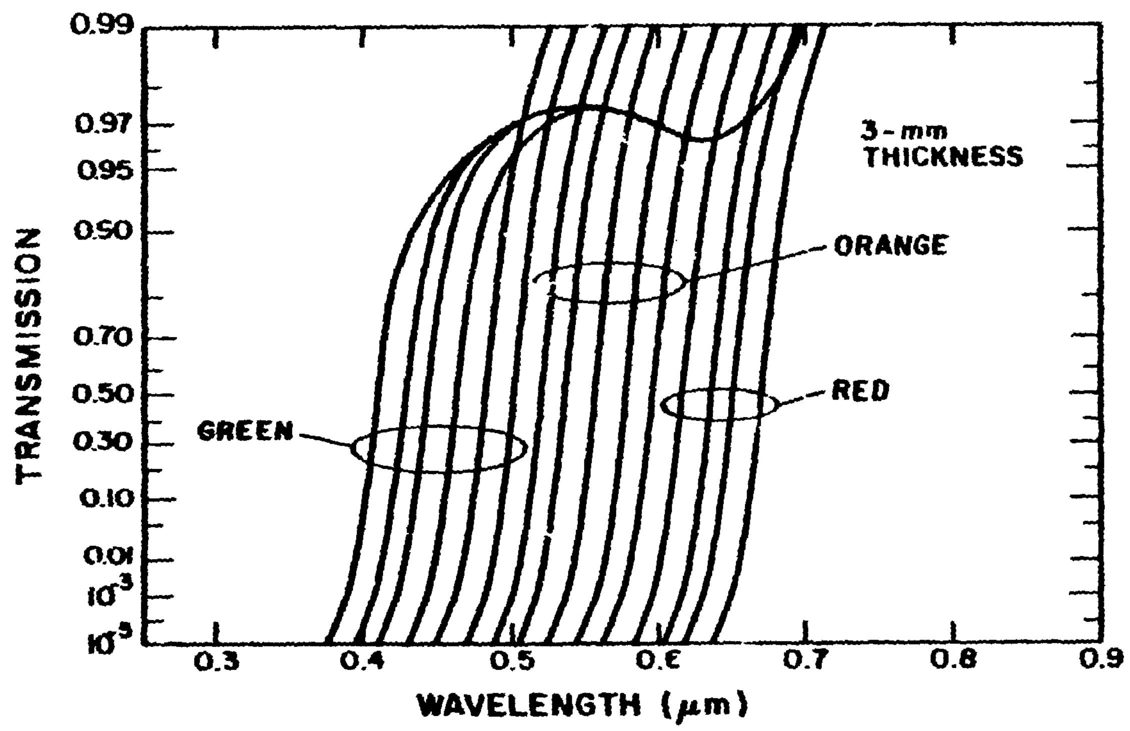

FIG. 4. Transmission curves for cut-off series color filters.

$$OD = \log_{10} \frac{I_i}{I_t} \text{, or}$$

$$5 = \log_{10} \frac{I_i}{10 \text{ mW/cm}^2} \quad \text{so that,}$$

$$I_i = 10^6 \text{ mW/cm}^2\text{, or } 1000 \text{ W/cm}^2 \ .$$

In this application, eye protection from HeNe radiation would require an OD of only 3 to be effective for a 10 W/cm^2 HeNe source. Because the damage threshold for skin is on the order of 10 W/cm^2 for HeNe, beams of higher power density should be enclosed.

Combination of Various Lenses in Double-Frame Spectacle

No single filter can protect over the range of wavelengths (0.2 to 16 μm) under study at LASL. A spectacle frame was, therefore, developed by FRO to accommodate two sets of filter glass lenses offering adequate protection over a wide range of wavelengths. For example, the frame and its interchangeable lenses can be used with ND:YAG and its harmonics. The clear glass, KG-3, as the primary lens (corrective, if desired), filters the 1.06-μm wavelength, and the orange glass, OG-550, as the second filter, filters all wavelengths below 0.53 μm produced by the doubled and higher frequencies (lower wavelengths). Luminous transmission is ~40%. (Broad-spectrum goggles are also available for dual-range absorption, but luminous transmission is low, on the order of 20%. This design of eyewear has limited use at LASL, i.e., for short term experiments and spectator wear only.)

LASER PROTECTIVE EYEWEAR POLICY AT LASL

General

All laser personnel at LASL undergo a preassignment eye examination. If laser output characteristics in a particular laboratory demands that a controlled area be established, laser personnel are informed of protective eyewear options for (1) individuals working routinely with the laser and (2) for visitors or short-term employees.

Preassignment Eye Examination of Laser Personnel

Laser personnel, according to ANSI Z136.1, are required to have a preassignment eye examination. Those working with lasers outside the ocular focus region of the spectrum need only an acuity test, which all LASL employees receive during their preemployment examination. However, laser personnel exposed to ocular focusable wavelengths (0.4 to 1.4 μm) are required to have their retina examined by an ophthalmologist, who follows the ANSI Standard protocol. A computer input form has been developed to permit recording of the results of the examination and recall on demand. No fundus photography is required, but may be performed for retinal pathology examination. Refraction measurements are made and corrective lenses are ordered, if necessary, in the special color filter glasses needed. The preassignment examination is the only medical surveillance required; however, LASL's Laser Personnel Registration Form contains information on laser characteristics, which is also entered into the data base so that an epidemiologic study of workers exposed to various wavelengths can be developed; if desired, further examinations of certain personnel may be indicated, i.e., periodic skin and eye examination of those with chronic ultraviolet exposure.

Analysis of Laser Environment for Classifying Personnel

Incidental personnel are defined in the ANZI 136.1 Standard as those "...whose work makes it possible but unlikely that they are exposed to laser energy sufficient to damage their eyes or skin, e.g., custodial, clerical, and supervisory personnel not working directly with laser devices." Laser personnel are those "...who work routinely in laser environments."

With regard to protective eyewear, the Standard requires protective eyewear "for Class 3 and Class 4 lasers ... whenever operational conditions may result in a potential eye hazard."

The criterion for requiring protective eyewear is clear: any person working routinely in a laser environment that could result in potential eye damage by exposure to the beam. Of course, spectators or visitors would be considered in this category during their stay in such an environment.

The following beam characteristics are defined by LASL as potential eye hazards and protective eyewear is required in their environment.

Laser Hazard Level for Eyewear

Wavelength, μm	cw, mW/cm^2	Pulsed, mJ/cm^2
0.2 - 0.4	50	All Lasers
0.4 - 1.4	10	All Lasers
1.4 - 16.0	300	All Lasers

The hazard levels listed are accessible emission levels at any position in the beam from the output window to the target or beam stop. Pulsed lasers require such low levels of energy density to cause damage that all pulsed lasers are categorized as potentially hazardous.

OPTIONS OF EYEWEAR STYLE

General

After establishing the need for eyewear by evaluating each laser's environment, a discussion is held with each employee to determine which eyewear is preferred. The following properties are compared in a discussion of the options and tradeoffs for each wavelength or range of wavelengths.

Comfort

Comfort is of prime concern. Spectacle frames (Fig. 5.) are the most popular, and, if side shields are not desired by the wearer, any style of safety frame is permitted. (The small solid angle of protection provided by side shields does not warrant insistance on their use.) Noncorrective, or "plano," lenses of the Schott series of filter glasses are available in stock to demonstrate the frame fit and luminous transmission of the color filter. Spectacles with plano lenses are available for workers or visitors not requiring correction. The lenses and frames qualify as industrial safety eyewear and as laser beam filters.

Goggles are available at entrances to controlled areas for visitors who require correction; however, goggles are not recommended because they are uncomfortable and because of their generally lower visual transmission. One reported accident* that caused permanent retinal damage occurred when a laser operator "...was not wearing protective goggles at the time, although they

*Laser Focus, August 1977 (under "Comment").

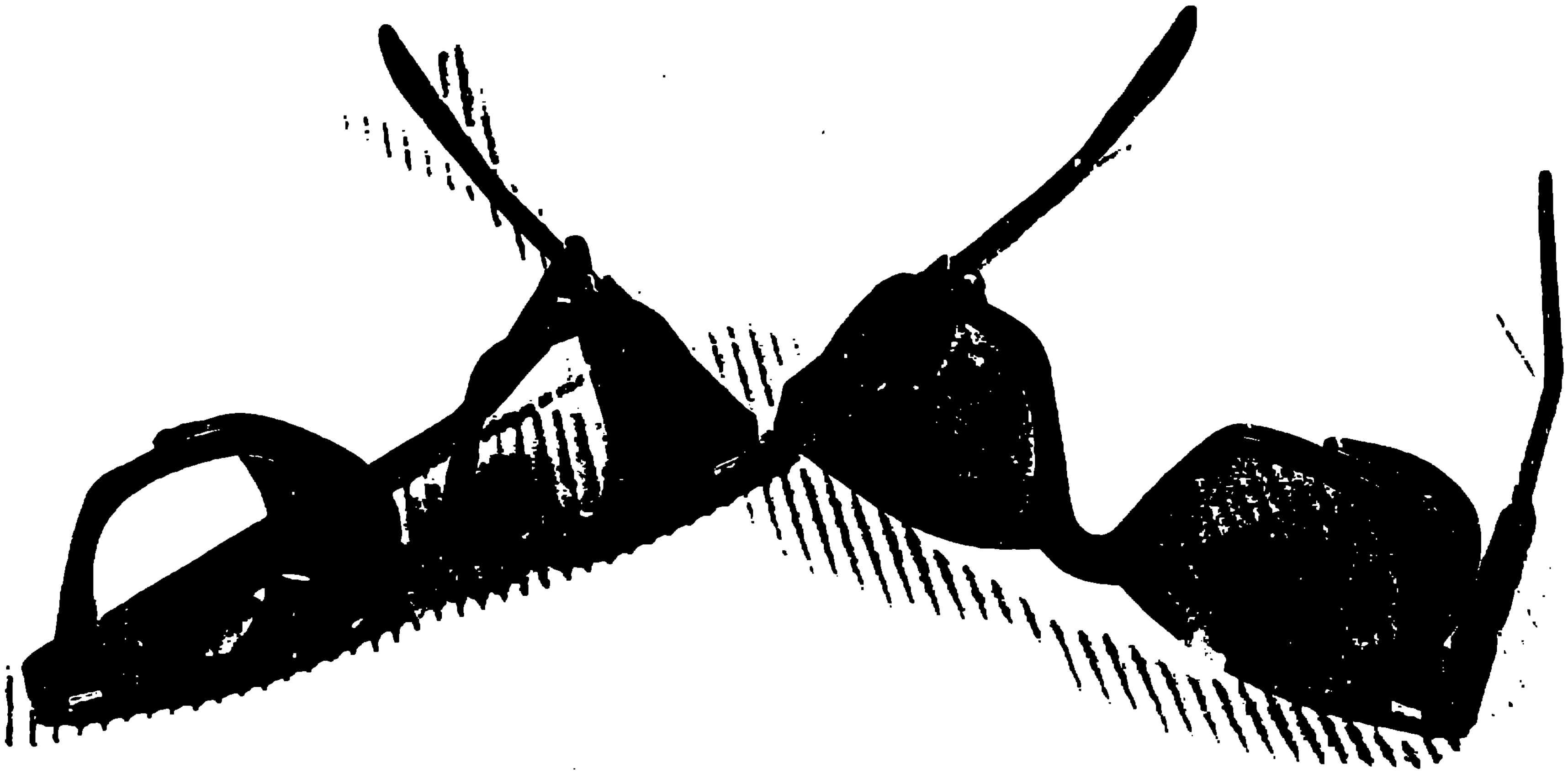

FIG. 5. Spectacle frames containing colored filter glass lenses: KG-3 on left; and BG-18 on right.

were available in the laboratory. As any experienced laser researcher knows, goggles not only cause tunnel vision and become fogged, they become very uncomfortable after several hours in the laboratory." These words from an experienced experimentor should be sufficient testimony to the value of the more comfortable spectacle type eyewear when laser personnel are required to wear protective devices for extended periods.

Luminous Transmission

It is very important to have good visibility while wearing laser protective eyewear. By selecting a filter glass, the laser user has the option of trading off luminous transmission for attenuation.

For example, the 3-mm-thick BG-18 filter has an optical density (OD) higher than 10 for Nd:YAG; and has a luminous transmission of 0.65% compared to an OD of 4.5 for KG-3, but the visibility through the KG-3 filter is almost 90%. The use of KG-3 is encouraged for Nd:YAG, because the OD is adequate. Another advantage is that KG-3 does not absorb the red lights on control panels, etc.

Side shields on spectacles are recommended only if the user's application of the beam requires close proximity to the beam, especially in the target area. However, the solid angle of accessible space at the side of the eye, reduced by the side shield, prevents good peripheral vision required for routine procedures in a laboratory environment. It is highly probable that a beam could enter the small solid angle and reach the macula (critical for vision), even when reflected (few %) from the back of the glass. Rather than wearing side shields, it is much more important that laser personnel wear a protective device that covers over 90% of the solid angle available to the cornea.

Attenuation or Filterability

Inexperienced laser personnel will often select protective eyewear without understanding optical density of filters relation to biological damage threshold values of the laser being employed. (See discussion of optical density, above). The logic involved in selecting a glass or plastic with as low an optical density as possible is to gain as high a luminous transmission as possible. Overprotection of the eye will not change the characteristics of the laser. Excessive optical density, generally any value over five for ocular-focusable laser users, is avoided so that hazardous laboratory operations can be carried out with adequate visibility. If the beam can cause skin damage, it should be enclosed or operated by remote control.

Cost Effectiveness

It is difficult to price the various laser protective devices, but the qualities of several general types can be compared. Durability is the most important property of any product in considering cost effectiveness. Any glass filter of the Schott Optical Glass Co. phosphate series described in this paper can be heat-treated (hardened) to pass the ball-drop test required by ANSI Z87.1. A scratch-resistant surface results. Also, the glass filters do not bleach, even at beam energy densities near damage values, and the failure mode is by cracking rather than melting.

Plastic filters for laser eyewear are not scratch-resistant, have a tendency to attract dust by static electrical charges in dry atmospheres, and will bleach, or even melt, if exposed to high levels of laser illumination. These undesirable properties require more frequent replacement than glass lenses, so that, although most current prices of plastic eyewear are lower than those of glass spectacles, glass filters are more cost-effective for long-range use in laser protection.

Another important consideration is the size of the various eyewear and the care taken in protecting the filter surfaces when not in use. The filter glass spectacle can be contained in a pocket case and carried by the owner whose name is inscribed on a temple. The eyewear is the individual's private property. Plastic eyewear has a tendency to be left on lab benches and other surfaces that contribute to wear and deterioration of filter surfaces by physical or chemical processes.

The well-being of the individual cannot be assessed in dollars and cents when evaluating comfortable, corrective eyewear with good luminous transmission, but this aspect of laser protective eyewear should be considered by management when approving laser eyewear procurement policies. The principal concern, of course, is the cooperation of the employee to wear the protective eyewear when a laser hazard is present in the assigned environment.

CONCLUSION

The selection of protecive eyewear for filtering hazardous laser beams in a laser laboratory environment should be approached with caution. The laser user should be knowledgeable, not only about the characteristics of the laser such as wavelength and beam intensity, but also should be informed about the biological (eye and skin) damage thresholds of the laser beam. The selection then can be made from the eyewear available for the particular wavelength employed, considering optical density vs luminous transmission, goggle vs spectacle styles, and, most important, greatest comfort for the individual.

The Los Alamos Scientific Laboratory policy on selecting laser protective eyewear permits the laser user to make the final decision as to style, within the constraint of using approved industrial safety frames.